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Summary of work on  
"LIQUID AND SOLID ION PLASMAS"  
(FY '91)

submitted to

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## ONR SUMMARY ON "LIQUID AND SOLID ION PLASMAS"

### I. INTRODUCTION

In these experiments, performed at the National Institute of Standards and Technology, Boulder, Colorado, atomic ions are stored in combinations of electric and magnetic fields. The resulting nonneutral ion plasmas can be viewed as one component plasmas where global equilibrium is obtained over long times (many hours). The use of atomic ions allows laser cooling, where the temperatures of the plasma can be reduced to 10 mK or less. For the densities typically achieved (up to  $10^{10} \text{ cm}^{-3}$ ) the plasmas become strongly coupled with coupling parameters  $\Gamma$  in excess of 100. The same lasers can be used to impart angular momentum to the plasma which provides a convenient method to control the density. The laser light which is scattered from the ions can also be observed in an imaging camera so the photographs and real time videos of the plasma can be made. Finally, by measuring the spectra of certain transitions in the ions, we can extract Doppler shifts and Doppler broadening which allows us to determine plasma temperature and rotation frequencies (and therefore, densities). Current efforts are devoted to applying these techniques to the measurement plasma dynamics and spatial correlations in ion plasmas.

### II. SUMMARY OF PROGRESS IN FY '91

#### A. Electrostatic Modes of a Spheroidal Penning Trap Plasma

We have continued to carry out work on the quadrupole modes of a spheroidal Penning trap plasma. In the limit that the Debye length  $\ll$  plasma dimensions  $\ll$  trap dimensions, a nonneutral plasma in a Penning trap has constant density with a sharp, spheroidal boundary. The electrostatic modes of such a plasma can be calculated analytically and are characterized by two integers ( $\ell, m$ ). The indices  $\ell$  and  $m$  refer to a description of the modes in spheroidal coordinates, with  $m$  describing the azimuthal variation (angle variable  $\phi$ ) and  $\ell$  the variation along a spheroidal surface in a direction perpendicular to  $\phi$ . In our trap we are able to excite a (2,0) mode by applying a sinusoidal potential to the ring (central) electrodes of the trap. In a (2,0) mode, the plasma always stays spheroidal, but the plasma aspect ratio (the length/diameter of the plasma) oscillates in time. We are also able to excite the static (2,1) mode by tilting the trap symmetry axis with respect to the magnetic field axis. There are three (2,1) modes. In each of these modes the plasma keeps its equilibrium shape but is tilted (or rotated) with respect to the magnetic field axis ( $z$  axis) of the trap. The tilted plasma then precesses about the magnetic field axis at the mode frequency. In a frame of reference rotating with the plasma, one of these modes precesses in a direction opposite to the plasma rotation and for a particular rotation frequency can be a zero frequency mode in the lab frame. We are able to excite only the static (2,1) mode because our electrodes are not split into azimuthal sections which would permit more general asymmetric drives.

With radiation pressure from two lasers we remove energy and control the angular momentum of a plasma of  ${}^9\text{Be}^+$  ions. As reported in our recent publication (D. J. Heinzen, et al., Phys. Rev. Lett. 66, 2080 (1991)), the static (2,1) mode was excited on a plasma of 2000  ${}^9\text{Be}^+$  ions at  $B = 0.82$  T when the plasma rotation frequency was increased to the rotation frequency where the (2,1) mode is static. Excitation of this mode produced a heating of the ion plasma. This past year we have also been able to spin up plasmas consisting of 40000  ${}^9\text{Be}^+$  ions at  $B = 6$  T ( $\Omega({}^9\text{Be}^+) = 10.2$  MHz). With care we could obtain rotation frequencies  $\omega > \Omega/2$  and ion densities near  $10^{10}/\text{cm}^3$ . The (2,1) heating resonance was observed to be very strong. Our alignment mechanism for the trap was not good enough to align the trap so that heating due to the (2,1) mode could be avoided. We also observed additional heating resonances at rotation frequencies less than the (2,1) heating resonance. These additional resonances presumably correspond to higher order static resonances which have recently been calculated by Prof. Dan Dubin at UCSD. They have the effect of limiting the plasma density to even lower values than the static (2,1) resonance. This has important implications for work where large numbers of charged particles are to be stored in a Penning trap.

In addition to measuring the (2,0) plasma mode, we have also detected and measured the (2,0) upper hybrid mode. This work was done at  $B = 0.82$  T. Both the plasma and upper hybrid (2,0) modes determine the plasma rotation frequency and aspect ratio. Therefore measurement of these modes may be useful in experiments with trapped positrons and antiprotons where other nondestructive means of obtaining this information is not available. We have done some calculations which provide the plasma rotation frequency (and therefore the density and aspect ratio) for a measured (2,0) mode frequency. This will be included in a future publication. We have also observed the actual oscillation which the plasma undergoes when the (2,0) plasma mode is excited. This was done by detecting the ion fluorescence from the radial edge of the plasma in coincidence with the sinusoidal drive applied to the ring electrodes. The drive is used to excite the mode. A zero crossing of the drive triggered a start pulse of a time to amplitude converter. A stop pulse was generated by a detected photon. In this way a histogram of photon counts as a function of time was obtained which showed the plasma radius oscillating at the drive frequency. This technique could be used in the future to observe the damping of the modes after the drive is turned off.

#### B. Linear Paul Trap

We have constructed an rf (Paul) trap like the one shown in Fig. 1. In this trap, the rf electric fields are transverse to the trap axis for the entire  $z$  extent of the trap. If a cigar shaped plasma is confined in such a trap, the "rf heating" caused by the micromotion is reduced relative to that in a quadrupole rf trap because the heating is caused only by the ions which are displaced from the  $z$  axis. If the diameter of the plasma is small the rf heating will be small. This may eventually allow us to study strongly coupled plasmas on large numbers of ions in a ponderomotive force (rf) trap.

In Fig. 2a, we show a string of  ${}^{199}\text{Hg}^+$  ions confined in a linear trap with rod diameters 1.60 mm and distance of the rod centers from the  $z$  axis of the trap equal to 1.55 mm. The spacing of the ions is approximately 20  $\mu\text{m}$ .

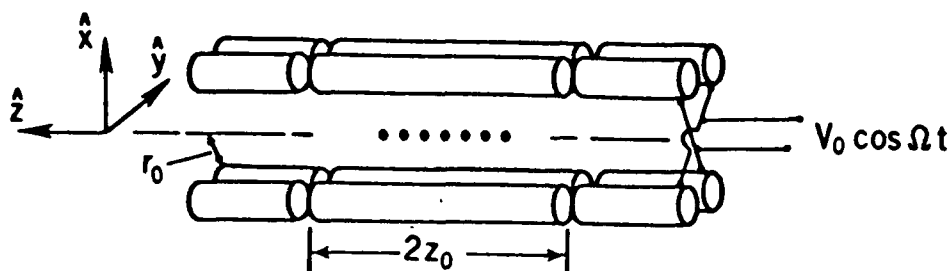


Fig. 1. Linear trap configuration. The alternating rf voltage  $V_0 \cos \Omega t$  is applied to diagonally opposing electrodes as shown. We assume the end portions of the electrodes are long enough that the resulting rf potential at the position of the ions is independent of  $z$ , so that the rf electric fields are parallel to the  $x$ - $y$  plane. To trap ions along  $z$ , the center four electrodes are held at static ground potential and the two sets of four electrodes on either end are held at a static potential  $U_0$  ( $U_0 > 0$  to trap positive ions). The average position of the ions could be made to coincide with the rf electric field null by applying slightly different static potentials to the four central rods to correct for offsets from contact potentials, etc.

When the linear density of ions is increased by increasing the static voltage applied to the end sections of the rods, or when the  $x$ - $y$  potential is weakened, zig-zag structures like those shown in Fig. 2b result. These structures are the lowest energy configurations expected for a certain range of the ratio of  $z$  confining potential and  $x$ - $y$  potential.

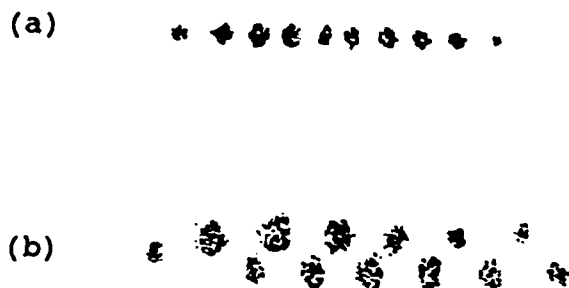


Fig. 2. Images taken of crystallized structures of  $^{199}\text{Hg}^+$  ions in a linear rf trap like the one of Fig. 1. In (a), 10 ions form into a string with length  $220 \mu\text{m}$ . In (b), the the lowest energy configuration for 13 ions is a zig-zag structure. In (a) and (b), the trap conditions are different but the magnification is the same.

The crystalline structures we have observed are closely related to the structures expected for cold ions in ion storage rings. With improvements in the trap design, we hope to be able to confine much larger numbers of ions and more closely approximate the conditions realized in ion storage rings.

### III. PUBLICATIONS ETC.

#### A. PAPERS PUBLISHED IN REFEREED JOURNALS

1. "Quantum-limited cooling and detection of radio-frequency oscillations by laser-cooled ions," D. J. Heinzen and D. J. Wineland, Phys. Rev. A42, 2977 (1990).
2. "Rotational equilibria and low-order modes of a non-neutral plasma," D. J. Heinzen, J. J. Bollinger, F. L. Moore, W. M. Itano, and D. J. Wineland, Phys. Rev. Lett. 66, 2080 (1991).
3. "Progress at NIST towards Absolute Frequency Standards Using Stored Ions," D. J. Wineland, J. C. Bergquist, J. J. Bollinger, W. M. Itano, D. J. Heinzen, S. L. Gilbert, C. H. Manney, and M. G. Raizen, IEEE Trans. on Ultrasonics, Ferroelectrics, and Frequency Control 37, 515 (1990).

#### B. PAPERS SUBMITTED TO REFEREED JOURNALS (not yet published)

1. "Sisyphus cooling of a bound atom," D. J. Wineland, J. Dalibard, and C. Cohen-Tannoudji, submitted to JOSA B.
2. "Linear Trap for High Accuracy Spectroscopy of Stored Ions," M. G. Raizen, J. C. Bergquist, J. M. Gilligan, W. M. Itano, and D. J. Wineland, J. Modern Optics, special issue on the Physics of Trapped Ions, ed. by R. Blatt, P. Gill, and R. C. Thompson, submitted.
3. "Experiments with ionic crystals in a linear Paul trap," M. G. Raizen, J. M. Gilligan, J. C. Bergquist, W. M. Itano, and D. J. Wineland, Phys. Rev. A, submitted.

#### C. BOOKS (and sections thereof) PUBLISHED

1. "Progress at NIST on Absolute Frequency Standards Using Stored Ions," D. J. Wineland, J. C. Bergquist, J. J. Bollinger, W. M. Itano, D. J. Heinzen, S. L. Gilbert, C. H. Manney, M. G. Raizen, and C. S. Weimer, proc. 4th European Frequency and Time Forum, Neuchatel, 1990,

#### D. BOOKS (and sections thereof) SUBMITTED

1. "Penning trap experiments at the University of Washington and at NIST in Boulder," F. L. Moore, proc. of the International Symposium on "Cooler Rings and Their Applications," Tokyo, Nov., 1991 (World Scientific, Singapore).
2. "Recent Experiments on Trapped Ions at the National Institute of Standards and Technology," D. J. Wineland, J. C. Bergquist, J. J. Bollinger, W. M. Itano, F. L. Moore, J. M. Gilligan, M. G. Raizen, D. J. Heinzen, C. S. Weimer, and C. H. Manney, Proc. of the Enrico Fermi Summer School on "Laser manipulation of atoms and ions," July, '91, Varenna, Italy, submitted.

3. "Laser Cooling of Trapped Ions," W. M. Itano, J. C. Bergquist, J. J. Bollinger, and D. J. Wineland, *ibid.*

E. INVITED PRESENTATIONS AT TOPICAL OR SCIENTIFIC/TECHNICAL SOCIETY CONFERENCES

1. OSA Annual Meeting, Boston, MA, Nov. '90, J. C. Bergquist.
2. International Symposium on Cooler Rings and Their Applications, Tokyo, Japan, Nov., '90, F. L. Moore.
3. 1990 Precise Time and Time Interval (PTTI) meeting, Tyson's corner, Va., Dec. 1990, D. J. Wineland.
4. 21st Winter Conference on Quantum Electronics, Snowbird, Utah, Jan. '91, J. C. Bergquist.
5. OE/LASE '91 Symposium on Laser Spectroscopy, SPIE, Los Angeles, CA, Jan. '91, J. C. Bergquist.
6. XIth Moriond Workshop, Tests of Fundamental Laws in Physics, Les Arcs, Savoie, France, Jan. '91, D. J. Wineland.
7. AAAS Meeting - symposium on Quantum Mechanics of Single Atoms, Washington, D. C., Feb. '91, D. J. Heinzen.
8. APS Spring meeting, Washington, D. C., April, '91, W. M. Itano.
9. Symposium on Frequency Control, Los Angeles, CA, May, '91, J. C. Bergquist.
10. Foundations of Quantum Mechanics, Santa Fe, NM, May, '91, J. J. Bollinger.
11. Workshop on Physics with Penning traps, Lertorpet, Sweden, June, '91, J. J. Bollinger.
12. Gordon Conference on Atomic Physics, Wolfboro, NH, July, '91, D. J. Wineland.
13. Enrico Fermi Summer School on Laser Manipulation of Atoms and Ions, Varenna, Italy, July, '91, D. J. Wineland.
14. Workshop in Honor of E. C. G. Sudarshan, Austin Texas, Sept., '91, W. M. Itano.

F. OTHER INVITED TALKS (colloquia, etc.)

1. Univ. of Colorado, Boulder, Co., Oct. '90, W. M. Itano
2. U. of Texas, Austin, Texas, Oct. '90, M. G. Raizen
3. Univ. of Alberta, Edmonton, Canada, Oct. '90, W. M. Itano
4. Argonne National Lab., Argonne, Ill., Oct. '90, J. J. Bollinger
5. Univ. of Colorado, Boulder, CO, Oct. '90, D. J. Wineland
6. Univ. of British Columbia, Vancouver, Canada, Nov. '90, W. M. Itano
7. U. C., Berkeley, Berkeley, Ca., Nov. '90, M. G. Raizen
8. Tokyo Metropolitan Univ., Tokyo, Japan, Nov. '90, F. L. Moore
9. Univ. of Electrocommunications, Tokyo, Nov. '90, F. L. Moore
10. Inst. of Nuclear Study, Tokyo, Nov. '90, F. L. Moore
11. Tohoku Univ., Sendai, Japan, Nov. '90, F. L. Moore
12. RCNP, Osaka, Japan, Nov. '90, F. L. Moore
13. Stanford Univ., Stanford, Ca., Nov. '90, M. G. Raizen
14. Weizmann Inst. of Science, Rehovot, Israel, Nov. '90, M. G. Raizen
15. Ben-Gurion Univ., Beer Sheva, Israel, Nov. '90, M. G. Raizen
16. Notre Dame University, IN, Nov. '90, J. J. Bollinger

17. Harvard Univ., Cambridge, MA, Nov. 1990, D. J. Wineland
18. Univ. of Colorado, Boulder, CO, Nov. '90, J. J. Bollinger
19. Johns Hopkins Univ., Applied Physics Lab., Laurel, MD, Dec. '90
20. Univ. of Rochester, Rochester, New York, Dec. '90, M. G. Raizen
21. Yale Univ., New Haven, CT, Jan. '91, J. J. Bollinger
22. Univ. of Oregon, Eugen, Oregon, Feb. '91, M. G. Raizen
23. Colorado School of Mines, Golden, CO., Feb. '91, M. G. Raizen
24. Stanford Univ., Stanford, CA, Feb. '91, D. J. Wineland
25. Univ. of Colorado, Denver, CO., Mar. '91, M. G. Raizen
26. Univ. of Texas, Austin, Texas, June, '91, M. G. Raizen
27. Univ. São Paulo, São Carlos, Brazil, 5 lectures, Aug. '91, D. J. Wineland.
28. Cornell Univ., Ithaca, N. Y., Sept. '91, D. J. Wineland.

G. HONORS, AWARDS, PRIZES

1. APS Fellowship, W. M. Itano
2. APS Fellowship, J. J. Bollinger
3. William F. Meggers Award (OSA), D. J. Wineland